

## Toward the next generation of air quality monitoring indicators



Angel Hsu<sup>a,\*</sup>, Aaron Reuben<sup>b</sup>, Drew Shindell<sup>c</sup>, Alex de Sherbinin<sup>d</sup>, Marc Levy<sup>d</sup>

<sup>a</sup>Yale School of Forestry and Environmental Studies, 195 Prospect Street, New Haven, CT 06511, USA

<sup>b</sup>Yale Center for Environmental Law and Policy, 195 Prospect Street, New Haven, CT 06511, USA

<sup>c</sup>NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA

<sup>d</sup>Center for International Earth Science Information Network, The Earth Institute, Columbia University, P.O. Box 1000 (61 Route 9W), Palisades, NY 10964, USA

### HIGHLIGHTS

- Our initiative bridges science and policy to design the next generation of air quality indicators.
- Ozone, mercury, particulate matter, and persistent organic pollutants are considered.
- Cross-cutting themes address knowledge gaps and needed investments in air pollution.
- Regional considerations of air pollution are addressed.
- Recommendations are made for what is needed to develop improved air quality indicators.

### ARTICLE INFO

#### Article history:

Received 16 March 2013

Received in revised form

12 July 2013

Accepted 15 July 2013

#### Keywords:

Air pollution

Indicators

Ozone

Particulate matter

Persistent Organic Pollutants

Mercury

### ABSTRACT

This paper introduces an initiative to bridge the state of scientific knowledge on air pollution with the needs of policymakers and stakeholders to design the “next generation” of air quality indicators. As a first step this initiative assesses current monitoring and modeling associated with a number of important pollutants with an eye toward identifying knowledge gaps and scientific needs that are a barrier to reducing air pollution impacts on human and ecosystem health across the globe. Four outdoor air pollutants were considered – particulate matter, ozone, mercury, and Persistent Organic Pollutants (POPs) – because of their clear adverse impacts on human and ecosystem health and because of the availability of baseline data for assessment for each. While other papers appearing in this issue will address each pollutant separately, this paper serves as a summary of the initiative and presents recommendations for needed investments to provide improved measurement, monitoring, and modeling data for policy-relevant indicators. The ultimate goal of this effort is to enable enhanced public policy responses to air pollution by linking improved data and measurement methods to decision-making through the development of indicators that can allow policymakers to better understand the impacts of air pollution and, along with source attribution based on modeling and measurements, facilitate improved policies to solve it. The development of indicators represents a crucial next step in this process.

© 2013 Elsevier Ltd. All rights reserved.

### 1. Introduction

Air pollution is one of the most pressing environmental concerns facing the world's nations today, dominating recent media headlines in both developing and developed countries alike. In China hundreds of flights were re-routed as “beyond index” air pollution and thick smog clouds forced the closure of Beijing's Capital International Airport in January 2013 (Wong, 2013). In 2011

populations in more than 160 Asian cities were routinely exposed to air pollution levels above those deemed safe by the World Health Organization (WHO); many experienced air pollution levels more than double recommended levels (CAI-Asia, 2012a). While air quality in the United States has been on average improving over the last several decades, individual episodes of high air pollution still occur, as residents of Salt Lake City learned in the winter months of 2013 when warm front inversions trapped vehicle exhaust in the city center for nearly a month (Frosch, 2013). The recent Global Burden of Disease project estimates that ~3.4 million deaths worldwide each year can be attributed to outdoor air pollution, especially particulate matter (Lim et al., 2012). This makes ambient air pollution the ninth most important contributor in the global burden of disease rankings.

\* Corresponding author. Tel.: +1 203 903 2199; fax: +1 203 432 0237.

E-mail addresses: [angel.hsu@yale.edu](mailto:angel.hsu@yale.edu) (A. Hsu), [aaron.reuben@gmail.com](mailto:aaron.reuben@gmail.com) (A. Reuben), [drew.t.shindell@nasa.gov](mailto:drew.t.shindell@nasa.gov) (D. Shindell), [alex.desherbini@ciesin.columbia.edu](mailto:alex.desherbini@ciesin.columbia.edu) (A. de Sherbinin), [marc.levy@ciesin.columbia.edu](mailto:marc.levy@ciesin.columbia.edu) (M. Levy).

Although air pollution is a global problem, its impacts are unevenly distributed across the world. Despite being “the most politically controversial environmental concern” because it “affects every resident, is seen by every resident, and is caused by nearly every resident,” responses to address pollution have varied by region, levels of economic development, and capacity (Mage et al., 1996). In countries throughout Europe and North America, successful air pollution control policies have led to dramatic improvements in air quality over the last few decades resulting in better public health and higher quality of life (Pope et al., 2009; Lim et al., 2012). In contrast, over the same time period air pollutant concentrations in developing countries, particularly in Asia, have risen dramatically, typically as a result of rapid industrialization and development. Seto et al. (2012) predict a high probability of a 185 percent increase in global urban land area extent by 2030, with nearly half of the growth forecasted to occur in Asia and predominantly in China and India. A result of this rapid industrialization is the increase of air pollution levels in cities (UNEP, 2012), although air pollution is still a problem in rural areas, particularly where indoor solid fuel use is still commonplace (Ezzati and Kammen, 2002; Smith and Mehta, 2003).

From the monitoring side, air pollution measurement is uneven and incomplete in many parts of the world, particularly where impacts are greatest. Chapter 40 of Agenda 21, the non-binding action plan agreed at the United Nations Conference on Environment and Development in 1992, called upon all nations to “develop the concept of indicators” and “to provide solid bases for decision-making at all levels” (UN, 1992). However, this charge has still not been met, and air quality data, often of low quality, “have failed to provide decision-makers and the public with the answers to basic questions especially concerned with human health and environmental impacts from multiple stressors” (Peterson and Williams, 1999; Srebotnjak, 2007). For example, measurements of air quality may be descriptive of concentrations, but ambient observations alone fall short of identifying sources as well as health effects and exposures for certain populations. For some pollutants, designing indicators that link pollutants to their sources are critical for abatement strategies. Moreover, when the right data are gathered, they are not necessarily collected in the right places. Data collection is unevenly distributed across the world, with more data available in developed countries while developing nation environmental managers face information shortfalls (Srebotnjak, 2007). The result is gaps in understanding of short-term, local and regional impacts of air pollution in addition to long-range, transboundary effects of air pollution, global trends, and projected impacts on particularly vulnerable populations in developing countries.

To respond to the need for more policy-relevant data and environmental indicators based on data available at the national level for the global scale, the Yale Center for Environmental Law and Policy (YCELP) and the Center for International Earth Science Information Network (CIESIN) at Columbia University have worked together for more than a decade to develop national-level sustainability indices. The most recent product of this collaboration, the Environmental Performance Index (EPI), will be described later in this paper. Recognizing that the environmental data used to monitor the world’s resources and to construct the biannual EPI is imperfect at best, YCELP and CIESIN, along with the Asian Institute for Energy, Environment and Sustainability (AIEES) at Seoul National University launched an initiative to bring together scientific experts and policymakers to discuss how science can inform the design of the next generation of air quality indicators. In October 2012, AIEES hosted a conference, co-organized by YCELP and CIESIN, “Towards the Next Generation of Air Quality Indicators,” in Seoul, South Korea that brought together more than 20 scientists

and policy experts to provide recommendations for this collaborative effort.

The initiative introduced in this issue is the first of its kind in developing a coordinated effort to bridge the state of scientific knowledge on air pollution to design the “next generation” of air quality indicators. The purpose of this initiative is to identify the monitoring systems and modeling methods needed to produce better data for the assessment of air pollution impacts on human and ecosystem health across the globe. Although indoor air pollution poses significant health risks for many people around the world (Lim et al., 2012), we primarily consider outdoor air pollution in this issue. The four outdoor air pollutants considered in this issue take a detailed look at the current measurement and knowledge gaps associated with particulate matter, ozone, mercury, and Persistent Organic Pollutants (POPs), and present recommendations for needed investments in monitoring to provide improved data for policy-relevant indicators. These four pollutants were selected based on considerations of their adverse impacts on human health, as well as baseline data availability by which to assess these pollutants. The ultimate goal of this effort is to enhance public policy responses to air pollution problems by linking improved data and measurement methods to decision-making through the development of indicators that can allow policymakers to: understand the true scope of the problem; and implement improved policies that will reduce air pollution. However, these papers do not propose specific air pollution abatement policies; rather, the focus of this effort is on the development of targeted indicators that communicate air pollution issues to policymakers.

As such, this special issue aims to bring clear direction for two different groups of people. First, for scientists, it provides guidance on short-term actions related to monitoring and modeling and longer-term challenges that are “high priority” science tasks of relevance to policy communities. Secondly, the papers provide targeted activities for decision makers at different levels—from national to global—and divided into short and longer-term categories. As a policy synthesis, this paper presents a distillation of the policy recommendations and themes of “data needs” that build upon recommendations from scientists and policymakers who have contributed to the following four papers in this special issue. Common themes and challenges in the four air pollutant working groups are identified in this paper, while more detailed issues specific to each pollutant are discussed in the following papers.

This synthesis and the papers that follow represent a call for better attention to air pollution monitoring needs across the world, as well as a vision of what kinds of indicators might be developed in the coming years. In starting from a foundation of measurement and modeling needs for each pollutant, each paper establishes the state of scientific knowledge and technology, as well as information gaps for each pollutant. From identification of these gaps, these papers establish needed investments in monitoring, technology, and modeling that could lead to the design of the “next generation” of indicators for air quality. This synthesis also posits that indicator efforts can present data describing the state of the environment, improve the process of gathering that data and, ultimately, facilitate global environmental governance of air pollution. In the shorter term, an immediate result of this effort is the consideration of improved or new indicators for inclusion in the EPI, the next iteration of which is planned for release in January 2014.

This paper is organized as follows: Section 2 provides background information on air quality indicators and the specific case of the Environmental Performance Index (EPI). Section 3 synthesizes cross-cutting themes and recommendations for improving air quality monitoring and policy-relevant indicators for the air pollutants covered in the subsequent papers in this special issue: PM, ozone, mercury, and POPs. Section 4 summarizes the role of the EPI

in facilitating the development of the next generation of air quality indicators.

## 2. Air quality indicators

### 2.1. The evolution of air pollution indicators

No blueprint exists to specify which indicators derived from scientific measurements or monitoring will be the most salient for policymakers. As Bruno and Cocchi (2002) state, “Air quality monitoring by means of appropriate indices has been a recognized problem over the last 30 years. As far as we know, there are no standard rules to compute such indices.” Numerous efforts have been undertaken over the last several decades to create environmental indicators or indices to represent both air and environmental quality for the purposes of comparison over time and between locations (Bell et al., 2005). These indices, such as the Pollution Standards Index that was first introduced in the United States in 1976 by the Environmental Protection Agency (Ott and Hunt, 1976), have emerged as a way of combining information on multiple pollutants to communicate air quality data (e.g., poor versus good days) (Bell et al., 2005). Over time, indices have evolved to match new scientific information about the health impacts of air pollutants (e.g., the addition of an 8-h requirement for ozone in place of a 1-h standard), as well as changes in decision-making priorities (e.g. greater emphasis on human health rather than ecosystem impacts) (Bell et al., 2005).

Therefore, the evolution of air quality indicators for decision-making and policy purposes has emerged from growing scientific knowledge and understanding of pollutants and their impacts. Before the Convention on Long-range Transboundary Air Pollution (LRTAP) was established, only two out of 30 member countries thought that acid rain was a serious problem (Levy, 1993). Scientific efforts such as the Working Group on the Effects and the European Monitoring and Evaluation Programme (EMEP) helped place pressure on states through LRTAP to reduce air emissions that were clearly producing impacts beyond their borders (Levy, 1995).

In the case of LRTAP and the European example, scientific monitoring resulting in greater clarity of the scope of air pollution problems galvanized policy action. Indicators have aided this process by bridging the “science-policy” gap through synthesizing complex scientific information and presenting it to stakeholders and policy-makers in understandable ways. In air quality management, indicators and indices have been used to communicate to the public measures that relate concentrations of pollutants to health. For example, the Air Quality Index (AQI), produced by a coalition of U.S. government and tribal agencies, including the Environmental Protection Agency (US EPA), presents daily measurements of several major air pollutants in the US in an easy to understand color-coded six-tier system. Citizens following the AQI can know when strenuous outdoor activity is inadvisable (poor or hazardous air quality days), advocates can track deterioration of air quality and seek to hold managers and policy-makers accountable, and managers and policymakers can easily identify spatial or temporal hotspots of poor air quality. Indicators perform these services and many others, including: allowing users to compare different entities (different countries, for example), identify best and worst practices, discover underlying trends, and break policy impasses based on misrepresentations of scientific uncertainty (POINT, 2011; McNie, 2006; Bradshaw and Borchers, 2000).

Making the environmental data that result from these measurements accessible and meaningful to relevant decision-makers and stakeholders is perhaps equally critical to achieving the goals of good governance and environmental stewardship, which is one of the main reasons why decision-makers have increasingly

sought the use of indicators (Polfeldt, 2006; Radermacher, 2005). Scientific information is now widely believed to be a key prerequisite for policymaking (Dimitrov, 2003). Even in places that have good technical monitoring capacity, data often get lost in translation at the information to “management-action” interface (Peterson and Williams, 1999). Indicators both quantify information to make an issue more readily apparent and simplify complex phenomena to improve communication (Hammond et al., 1995). In situations where narrow assessments are called for, such as in gauging compliance with an ambient air quality standard for a single pollutant at a local level, indicators can be calculated from direct measures of source emissions to quantify pollution. Scaling up to more complex or large-scale comparisons, for example across nations or regions, and in situations when aggregating multiple facets of complex environmental issues, aggregate indices can combine disparate indicators for a different policy aim, as in the case of composite indices like the EPI, which we turn to next.

### 2.2. The Environmental Performance Index

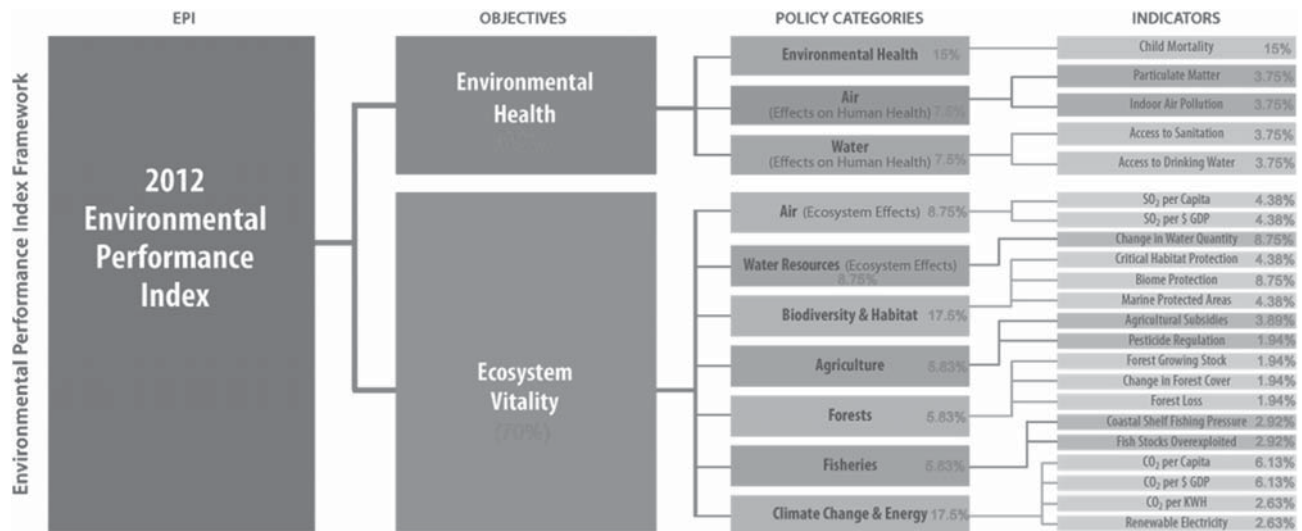
As mentioned in the introduction, an immediate aim of this synthesis and special issue is to identify new air quality indicators for the EPI, as well as what investments are needed for a “next generation” of indicators for air pollution management in a set of limited outdoor air pollutants. Therefore, a brief introduction of the EPI is provided in this section as a framework to understand existing air quality performance indicators based on globally-available national datasets. From the EPI, this initiative has sought to consider improved or ideal indicators that can provide a more complete picture of how environmental regulations are protecting human health and ecosystems from the effects of air pollution.

As a composite index, the EPI combines multiple tiers of indicators to assess country-level environmental performance with a score of 0–100 and a ranking relative to other countries. The EPI measures environmental performance in two core objectives of environmental policy: Environmental Health, which measures environmental stresses to human health, and Ecosystem Vitality, which measures ecosystem health and natural resource management. These two objectives reflect policymakers’ priorities with respect to environmental protection – measuring impacts on the human and natural dimensions of the environment. Performance is then gauged in ten policy categories, with 22 indicators across these categories for the 2012 EPI (Fig. 1).

#### 2.2.1. Outdoor air quality indicators in the EPI

The EPI and its predecessor, the Environmental Sustainability Index (ESI), have generally included two types of air pollution indicators: those based on ambient concentrations (current conditions) and emissions (flows). In the early versions of the ESI, from 2000 to 2005, indicators of outdoor air quality included measures of the “state” of urban air – sulfur dioxide (SO<sub>2</sub>), nitrogen dioxide (NO<sub>2</sub>), and Total Suspended Particulates (TSP); “pressure” measures for ecosystems, including the number of vehicles per square mile, and coal consumption per square mile; and “impact” measures such as the number of child deaths from respiratory illnesses. These indicators were based on sparsely populated datasets from the Air Management Information System (AMIS), World Bank, OECD, WHO, European Environment Agency, and Global Urban Observatory, which required significant data imputation in order to expand country coverage.

By 2006 the first pilot version of the EPI shifted from included data modeled by the World Bank on coarse particulate matter (PM<sub>10</sub>) estimates by city, and created population-weighted averages by country to assess outdoor air quality pressures on human



**Fig. 1.** The indicator framework of the 2012 EPI, including objectives, policy categories, and indicators. For further information on the methodology used to calculate the EPI, see Emerson et al. (2012). Indicators for POPs, mercury, and ozone were not included in the 2012 EPI, but instead were pollutants of interest for the initiative presented in this paper.

health. For ecosystem effects, the EPI from 2006 to 2010 included ecosystem ozone estimates. In 2008 SO<sub>2</sub> emissions per square kilometer of land area was added, and 2010 included Nitrogen Oxide (NO) and VOCs. Requiring historical time series data, the 2012 EPI excluded outdoor air quality indicators for ecosystem ozone, NO, and VOCs and instead included a measure of SO<sub>2</sub> emissions normalized by both population and land area (Smith et al., 2011). In terms of human-health related impacts, due to concerns of comparability in the PM<sub>10</sub> data from the World Bank, the 2012 EPI used a satellite-derived measure of fine particulate matter (PM<sub>2.5</sub>) that involved the conversion of MODIS Aerosol Optical Depth (AOD) to ground-based estimates using modeled algorithms by van Donkelaar et al. (2010).

The 2012 EPI still lacks a number of important measures of air quality, including estimates of ozone, due to the unavailability of ground-based measures in most countries and the lack of time series for modeled datasets. The EPI also does not include any indicators of toxic chemicals that are transported by air, such as mercury and POPs. These omissions, which are discussed in detail in each of the subsequent papers, are largely due to varying levels of capacity in countries to measure ambient concentrations of these pollutants.

### 2.3. The development of the next air quality indicators

From more than a decades' worth of experience developing the ESI and EPI, and consulting with decision-makers and air quality managers, the EPI team has identified a number of policy-relevant questions aimed at addressing shortcomings in the state of knowledge with respect to data on air pollution and indicators. These questions, posed here, were brought to the larger process identified in this paper and are included to display some of the open questions relevant from a policy-maker perspective, which may or may not overlap with the open questions salient to the scientific community:

- Are there common measurement challenges and knowledge gaps in PM, ozone, mercury, and POPs that can be generalizable for all, or are there unique properties to each that prevent comprehensive policies to address all broadly?
- What investments are needed to bridge technological divides, disparities in financial resources and capacity to achieve global coverage for monitoring these pollutants?

- What regional differences (e.g. variability in geography, industrialization, and climate) need to be taken into consideration to design indicators that are meaningful and actionable, both at the country level and cross-border?
- What international policies can be put in place to encourage data-sharing and transparency of air pollutant information to aid in collective action to tackle global air quality problems?
- What are the potential barriers, such as financial capital or political considerations, that may prevent improved measurement of air pollution or hinder the adoption of new indicators?

These questions guided the YCELP-CIESIN-AIEES effort to commission papers that address these challenges. The following section outlines a synthesis of these recommendations in relation to these critical gaps.

## 3. Synthesis and recommendations

The papers that follow this paper in this special issue present the analyses, findings, and recommendations of our air pollution expert teams for each major air pollutant of concern: PM, ozone, mercury, and POPs. What is included in this section is a synthesis of the major themes regarding data needs and policy recommendations that resulted from the conference and papers, presented not necessarily in order of priority or feasibility. Table 1 presents a summary comparison matrix of select science needs and related policy recommendations for each pollutant that were identified in each of the pollutant papers (Bowman, 2013; Engel-Cox et al., 2013; Hung et al., 2013; Pirrone et al., 2013).

### 3.1. Considerations of integrated monitoring across pollutants

It is clear that commonalities in the sources of different air pollutants may allow for significant synergies in managing pollution in an integrated and consistent manner, notwithstanding the different management considerations required by specific pollutants. A number of issues impede such synergized management however. In this special issue Hung et al. (2013) emphasize the need for integrated frameworks for maintaining long-term monitoring programs supported by a network of laboratories and monitoring stations at multiple scales – local, regional, and inter-regional. Such integrated networks can then provide coordinated responses when

**Table 1**

Select science needs and policy recommendations by pollutant.

Pollutant	Monitoring	Modeling	Other
PM	Improved ground-based monitoring is needed, particularly in developing countries where networks are sparse. New sensors that are cheaper and more durable need to be developed to expand these networks. Advances in satellite technology, such as multiangle spectro-polarimetric imagers, could provide more information to better identify the size and chemical species of aerosols. Simple personalized PM monitoring surrogates that use social media (e.g., phone apps that measure visibility) could open the possibility of crowd-sourced pollution monitoring.	Integration of models and remote sensing can improve algorithms to estimate PM <sub>2.5</sub> concentrations from satellite data. However, to improve the accuracy of these models, a global repository of <i>in situ</i> , ground-based PM <sub>2.5</sub> measurements are critical for error estimation.	Programs need to be tailored toward local conditions, yet follow global standards so they can be combined for global comparisons. More work is needed to convert air pollution measurements into values that represent population-wide adverse health outcomes and economic impacts.
Ozone	Geostationary and low-earth orbit satellite measurements hold promise for filling global ozone monitoring gaps. However, complimentary <i>in situ</i> measurements from the surface to middle troposphere are needed for satellite and model validation.	In order to utilize promising satellite and ground monitoring data, a global program to routinely assimilate new monitoring data into analytic products will be critical for pollution prediction, attribution, health assessment, and air quality-climate mitigation.	
POPs	Investments to maintain established and newly installed monitoring sites to improve global coverage and resolution (role for passive samplers). Long-term data with >10-year timescale will be necessary for identification of global trends.	Back-calculating emissions from measured air concentrations using environmental fate models can resolve emission inventory gaps. Expanding this approach to new locations and spatial scales should be a science/management priority. The relationship between emissions of mercury and resulting concentrations in seafood has not been quantified; nor has the global flux of mercury into and out of large ecosystems. Modeling efforts to predict and describe these links are underway but will require continued investment and, ultimately, novel measurements across varied geographies and marine organisms.	Too little is known about the distribution of POPs from emerging industries (e.g., e-waste) and relationship with co-pollutants (e.g., urban PM). Assessing risks from these sources should be a priority. Analysis and measurement of the re-emission of mercury into the atmosphere from legacy deposits represents an important new avenue of research. Management will require a better understanding of the contributions of particular human actions, such as biomass burning, to this re-emission process. There is a need to develop coordinated and interoperable management of data to foster complex data analysis, which includes atmospheric, marine and health information.
Mercury	Marine systems are a primary site of mercury deposition, re-emission, and human exposure. Limited data from offshore measurements makes trend monitoring and fate prediction difficult. Greater and more varied offshore mercury monitoring is called for. There is a need to monitor the concentration of Hg species and their deposition rates at remote locations for accurate future predictions of the impact of changing Hg emissions on the terrestrial and ocean environments		

new challenges with respect to air quality emerge. In the case of ozone and PM, shared precursors may mean that it makes sense for policymakers to address these pollutants in concert with a suite of other intermediary and secondary particles. Nitrogen oxide (NO) can lead to the formation of both PM and ozone, although ozone's formation from nitrogen oxides (NO<sub>x</sub>) are more complicated (Bowman, 2013; Engel-Cox et al., 2013). Fine PM also serves as binding agents for POPs and play an important role in "determining the fate of POPs in the atmosphere" (Hung et al., 2013). Therefore an understanding of POPs emissions in the atmosphere necessitates monitoring of fine PM. Additionally, the authors of each paper mention with regularity the need for established quality assurance/quality control (QA/QC) procedures to ensure that data collected are "consistent" and "comparable" amongst pollutants measured. In terms of financial investments, co-location of monitors for disparate pollutants may result in cost savings, particularly in terms of identification of activities that generate multiple pollutants from the same sources.

However, at the same time that integrated monitoring among pollutants is called for, each paper in our special issue identifies data and monitoring challenges unique to each pollutant that require special consideration. For both mercury and POPs, for example, the oceans serve as an important mechanism of transport, particularly so for mercury, a significant marine food chain bio-accumulator. This creates a different range and diversity of sites and actions requiring monitoring than PM, for example, which is largely an air and land-based issue. Development of air quality indicators for POPs also presents challenges unique from other air pollutants. As Hung et al. (2013) point out, although POPs are environmental contaminants that are often transported by air, which necessitate its monitoring in air, the adverse effects of POPs occur in terrestrial

and marine systems, so the primary impact is not a direct result of concentrations of POPs in the air. Therefore, in the creation of indicators, there is a mismatch between the measurement and the impacts whereas for other pollutants, such as PM and ozone, concentration measurements can be more directly linked to impacts.

### 3.2. Improvements to ground monitoring

Despite advances in remote satellite technology,<sup>1</sup> solid, ground-based measurement will always be required for detection of pollutants, health impacts, as well as for "ground-truthing" (calibration and validation) of satellite measurements. All of the authors stressed the need for better ground monitoring that can be roughly divided into calls for better data *coverage* (e.g., more sites, more measurements) and calls for better data *quality* (e.g., improved quality control protocols, more permanent measurement stations).

However, it is important to note that the current state of available ground-level monitors and networks for each pollutant varies widely. On a spectrum from the most available to least available ground-monitoring, most countries have some baseline measurements of PM, although monitors are unevenly distributed between developed and developing countries (Engel-Cox et al., 2013; Height and Ferrier, 2006; Brauer et al., 2012), less so for ozone. There exists fairly good coverage of ground-based monitors for POPs (see Figs. 1

<sup>1</sup> Engel-Cox et al. (2013) mention the launch of the Visible Infrared Imaging Radiometer Suite (VIIRS) in October 2011 that provides important datasets for PM. Bowman (2013) references a variety of satellites (NASA GEO-CAPE, ESA Sentinel 4, GEMS, and NASA-TEMPO) as well as a geostationary constellation of the sounders GEMS, Sentinel 4, and GEO-CAPE that will eventually allow for global air quality assimilation of ozone data.

and 2 in Hung et al., 2013), while only North America and Europe monitor mercury (Pirrone et al., 2013). In the case of ozone, particularly in developing countries and in Asia, ozone is not yet fully regulated, which explains the lack of ground-base monitoring (Bowman, 2013). Engel-Cox et al. (2013) state that ideally a permanent monitoring network should be established in each urban area and country that can be used for efficient local and national air quality management. Fig. 2 provides a summary of the uneven distribution of pollutant monitoring stations between developed (North American and Europe, or NAWE) and developing countries (non-NAWE).

Other key recommendations that emerge include:

- *Expanded coverage* – the papers consistently identify low temporal and spatial sampling and resolution in measurements and monitoring sites as an impediment to understanding the flow and reaction of pollutants of concern in the atmosphere. Hung et al. (2013) propose co-location of POPs air monitoring equipment at existing monitoring sites (a practice not yet common) to improve our understanding of the relationships among co-pollutants (such as ozone and POPs, or PM). Engel-Cox et al. (2013) emphasize PM monitoring stations distributed amongst a greater diversity of land-use sites, including city centers, commercial, residential, industrial, and near-urban areas to reveal hidden differences in PM concentrations and spread. For atmospheric mercury, which operates across large distances and time frames, Pirrone et al. (2013) identify the lack of “detailed and coordinated” measurements across the entire Southern Hemisphere as a major obstacle to tracking mercury movement and deposition. A permanent global monitoring network for mercury would be a desired next step. Bowman (2013) points to the necessity of ground-based monitoring in developing countries, particularly Asia, to allow for improved validation of satellite-based data.
- *Increased quality* – the authors also all raise the issue of potentially low data quality as an impediment to accurate atmospheric monitoring and, consequently, modeling. New or

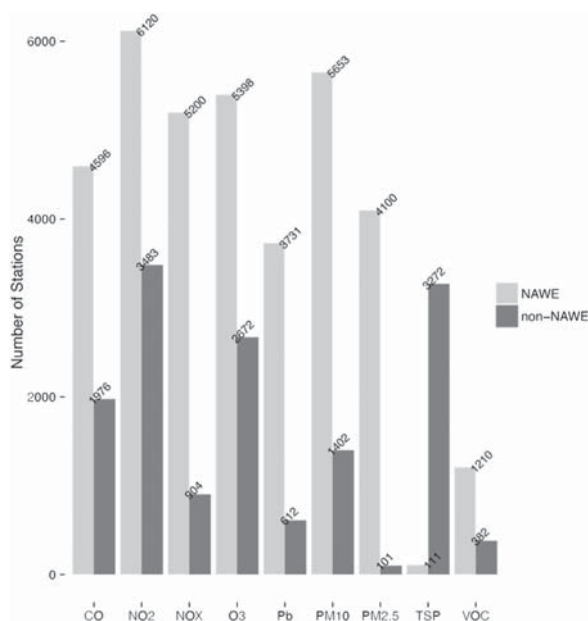


Fig. 2. Number of monitoring stations in developed (North America and Western Europe, or NAWE) versus developing countries (non-NAWE). Data source: Rudolph Husar and Stefan Falke, for GEO Task US-09-01a (Group for Earth Observations, 2010).

difficult measurement techniques, such as those being developed to identify and quantify specific mercury compounds in ambient air, offer particular data quality problems. Accurate reporting of ancillary measurements that impact air pollution is also critical for improving the quality of data, as in the case of PM, which is influenced by relative humidity. As Engel-Cox et al. (2013) mention, accurate data on relative humidity is necessary to convert satellite retrievals of AOD to ground-level PM<sub>2.5</sub> mass concentrations. However, consistent reporting of relative humidity is not yet standard practice. The development of standardized quality control protocols to be used across global monitoring sites may resolve these issues, allowing for “consistent and comparable” data.

### 3.3. Improved integration of ground and aerial/satellite measurements

A consistent theme throughout the papers is the need for integration of data, particularly between ground-level and aerial/satellite measurements. Assimilation of ground data and satellite measurements are essential for improving and verifying the accuracy of both sources of data. For PM and ozone, recent and planned advances in satellite technology and deployment represent perhaps the most promising development in the effort to improve monitoring and measurement of these pollutants across the globe. However, satellite monitoring is not a feasible option for either POPs or mercury. While Pirrone et al. (2013) state that satellite monitoring might be technically feasible in principle, very low concentrations in the troposphere render it too complicated for remote sensing.

Alongside these advancements have come calls for:

- *Increased attention to improving consistency across satellite measurements.* The portfolio of active and planned satellites producing air pollution data have, by necessity of different launch dates and different programmatic goals, multiple and at times divergent measurement instruments. Making the data gathered from these instruments comparable for analyses and compatible for aggregation into an index will do much to improve their policy impact. As the papers following this report present, clear estimates of measurement accuracy and error and new methodology for integrating models with remote sensing will be a part of this process.
- *Integration of satellite and in-situ measurements.* For PM, there are still uncertainties with respect to models that assimilate satellite measures to estimate ground-level concentrations. In van Donkelaar et al. (2010), ground-level estimations of PM<sub>2.5</sub> have an uncertainty of 25 percent within 1 standard deviation, based on errors and sampling from AOD retrieval and in the aerosol vertical profile. Kinne et al. (2003) note the difficulty in validation of aerosol modules. For the recommended constellation of geostationary satellites planned for global ozone monitoring, as highlighted by Bowman (2013), integration of satellite and *in situ* data into a global assimilation system will be critical, with the Global Monitoring for Environment and Security (GMES) program serving as an example.

### 3.4. Further modeling

The authors of the papers in this issue all emphasized the importance of modeling in generating pollutant data, filling gaps, understanding important transport pathways and processes, as well as supporting and improving the accuracy of satellite measurements. Ground monitoring will, by nature of costs and geographic impediments, never expand to completely cover all important airways. Additionally, as Engel-Cox et al. (2013) note,

satellite observations will never offer “continuous measurements” of certain pollutants in some contexts, such as ground-level PM mass in urban centers. Modeling will thus continue to be an important aspect of environmental sensing and description. In particular, modeling to achieve the following goals will be important:

- Relating satellite observations with ground-level concentrations;
- Predicting the transport and long-term atmospheric movement/changing states and composition of emitted pollutants;
- Determining the relative contributions of specific sources and countries to global pollutant burdens, particularly for pollutants susceptible to long-range transport; and
- Describing the links between pollutant deposition, chemical reaction, uptake by organisms, and public and environmental health outcomes (particularly for methyl mercury).

For some pollutants, such as mercury and POPs, modeling is required to produce data for indicators where direct monitoring for policy-relevant indicators do not exist. Due to the indirect link between most atmospheric mercury measurements, which are only available in North America and Europe, Pirrone et al. (2013) state that modeling is also needed to link emission to impacts, as there is an inability to directly develop an indicator based on atmospheric mercury measurements and impact on humans. Observations, when coupled with modeling can provide estimates of ecosystem mercury fluxes, which means that the challenge for a next generation air quality indicator would be to link these changes in emission to changes in fluxes and ecosystem loadings, and finally to impacts (Pirrone et al., 2013). For all pollutants, modeling is also necessary to help attribute air pollutant levels to emissions in specific countries and from specific sources. Using inverse-modeling from measured air concentration data from air monitoring programs and networks, country-level indicators can be constructed. However, Hung et al. (2013) note the difficulty of correctly attributing POPs emissions in globalized production and supply chains, whereby POPs resulting from e-waste may not be properly accounted for if electronics are produced in one country and then disassembled in another.

### 3.5. Data sharing and accessibility

In direct relation to a need for integrated response to common-source pollutants there is a general need, in the effort to improve global air monitoring, for integrated data storage across monitoring networks, entities, and methods. The development and maintenance of one universal and universally accessible global air pollutant data archive could do more, perhaps, to advance global air pollution understanding and research than nearly any other single intervention. Engel-Cox et al. (2013) point out, for example, that creating a global repository for satellite *in situ* PM measurements would go a long way to assisting in the science of developing much needed global error evaluation methods for PM satellite monitoring. Hung et al. (2013) refer to existing atmospheric pollutant data archives, such as the Arctic Monitoring and Assessment Program (AMAP)/European Monitoring and Evaluation Program (EMEP) database, which can facilitate data sharing and provide a foundation for model and indicator development for POPs. Bowman (2013) also recommends support of international agreements or infrastructure to encourage transparency and sharing of available ground-based ozone measurements. A similar, or even the same network for PM would also greatly facilitate analysis of worldwide particulate level trends and variations. Such global, universal archives could be well-placed, additionally, to accept new

datasets, from ground networks or satellites, and help evaluate new monitoring methodology.

An example of global principles to guide open data and information sharing is in the Global Earth Observation System of Systems (GEOSS) 10-Year Implementation Plan Data Sharing Principles,<sup>2</sup> which state:

- There will be full and open exchange of data, metadata and products shared within GEOSS, recognizing relevant international instruments and national policies and legislation;
- All shared data, metadata and products will be made available with minimum time delay and at minimum cost;
- All shared data, metadata and products being free of charge or no more than cost of reproduction will be encouraged for research and education.

However, there are barriers to implementing such sharing principles, in terms of both financial and technical capacity, and political considerations that may prevent free exchange of data and information. These issues are addressed on a pollutant-by-pollutant basis in greater depth in the following papers in this issue.

### 3.6. Better communication

Though communication on air pollution issues, to decision-makers and the public at large, is generally good, there is room for improvement. While abatement technology and emissions control policies are available to improve air quality, stakeholders and vulnerable individuals still suffer public health risks. Engel-Cox et al. (2013) note that without greater adoption and application of PM data and advisories by stakeholders of all kinds (e.g. the public, policymakers, scientists), there will be only a limited impact on solving the major health effects caused by PM pollution. The authors point to using “principles of open science and crowdsourcing” to engage the public in air pollution monitoring (asking them, for example, to take visibility measurements through mobile phone pictures) and thereby achieve the dual values of increasing monitoring and increased awareness of public health risks. Integrating such novel communication methods and research tools into other pollutant monitoring schemes, say for those of mercury in fish tissue, may help fill some of the science gaps mentioned throughout this report. The Natural Resources Defense Council (NRDC) features a Mercury Calculator on its Consumer Guide to Mercury in Fish website<sup>3</sup> to help consumers understand different levels of mercury in various fish species and determine whether they are consuming dangerous levels of mercury. Linking ambient mercury emissions in the air and levels in fish species may help to raise public awareness to push for better regulation and monitoring of ambient mercury emissions.

### 3.7. Regional considerations

Air quality, in terms of pollutant sources, composition, and impacts, varies by location and scale. In addition, a city, country, or region’s ability to both monitor and abate air pollution differs according to context. A common theme in the elaboration of regional considerations in each of the papers is the rapid industrialization of developing countries in Asia and Latin America that will drive much

<sup>2</sup> The GEOSS Data Sharing Principles and working documents can be accessed: [http://www.earthobservations.org/geoss\\_dsp.shtml](http://www.earthobservations.org/geoss_dsp.shtml). Last accessed: February 28, 2013.

<sup>3</sup> NRDC’s Mercury Calculator is available: <http://www.nrdc.org/health/effects/mercury/guide.asp>. Last accessed: February 28, 2013.

of the changes in global air pollution. In China alone, it is estimated that 1 billion people will live in urban centers by 2025 and the country will have 221 cities with more than 1 million inhabitants each (MGI, 2009). The pace and scale of urbanization in these areas will be responsible for generating air pollution that will have global ramifications. A recurring theme in all of the papers is the trans-boundary nature of each of the pollutants, implying the need for coordinated, global efforts by which to address each both locally and globally. Pirrone et al. (2013) note that reducing atmospheric

mercury deposition in the ecosystem hinges on both reducing global levels of mercury and also local sources. However, these links between local and regional emissions and exposure are not direct, as exposure relies on another mechanism dependent on dietary habits and seafood consumption, which is made even more complicated by globalized food supply chains and commodities transfers.

While the idea of “regions” are often defined in geopolitical terms, Hung et al. (2013) include an additional concept of regionally

**Table 2**

Select pollutant-specific issues to be considered in the next generation of air quality indicators.

Pollutant	Relative importance of emissions source vs. transport and re-emission	Importance of temporal and spatial scales	Importance of interactions with other pollutants
PM	Both local and long-range transport of PM are critical. PM can travel long distances to affect other regions. In a localized area, PM, in particular fine PM or PM <sub>2.5</sub> affects human health near the source where it is emitted.	PM impacts local conditions and can also be transported long distances to produce regional and global effects. Photochemistry can alter PM over both distance and time.	Secondary PM is formed in chemical reactions with SO <sub>2</sub> and NO <sub>x</sub> in the atmosphere. PM is also a binding agent for POPs.
Addressed by current indicators?	Current indicators include both emissions at industrial sources and ambient pollutant concentrations. Ambient conditions are most relevant to health and are the most widely communicated. They do not differentiate from pollution sources that may be nearby or from longer distances.	Major PM events tend to be daily or over multiple days and often cover cities or regions; these are well documented in the indicators. However, small spatial scale differences in PM, such as street level pollution or local industry emissions, are not well measured by indicators. For example, a city overall may have low levels of PM, but residents in a house close to a busy road may experience high PM levels. There are also very few good indicators of indoor air pollution, which is most important where cooking and heating still come from biomass burning.	The indicators do not address PM chemical composition, or PM interactions with other pollutants, both of which may have different impacts. Impacts of PM on human health through climate change are not currently addressed.
Ozone	Surface ozone comes from a combination of natural and anthropogenic sources, which may be a combination of both local and distant sources. Real-time information on ambient ozone and precursor concentrations may be more important (in the short-term) for indicators than emission source information.	Ozone has both short-term and long-term health impacts. Long-term health is driven by background concentrations, which are influenced by distant sources and are especially sensitive to methane, whereas short-term impacts are driven by local sources and shorter-lived precursors. Distinguishing the two requires global and high spatio-temporal resolution measurements.	Ozone is not directly emitted but forms from precursor pollutants (NO <sub>x</sub> , CO <sub>2</sub> , VOCs and CH <sub>4</sub> ). Monitoring and modeling of both ozone and its precursors is necessary for attribution and control.
Addressed by current indicators?	Ozone is routinely monitored and regulated in many countries. The impact of ozone on human health through climate change is not currently addressed.		
POPs	Emissions represent “the most relevant indicator for the relative burden of POPs that a country or region contributes to the global atmosphere” (Hung et al., 2013). Improving regional emissions inventories will be critical for robust POPs indicators.	POPs in air can affect exposure on the local scale (e.g. in cities), as well as on the global scale (e.g. long-range transport to polar and cold mountain regions). Monitoring temporal trends is important in assessing effectiveness of control measures. It is important to achieve broad total coverage (large scale and long time frame).	Many POPs are PM-bound and therefore understanding the relationship between POPs and PM transport, persistence (when associated with PM), deposition, and exposure is critical to managing health risks. Incorporating this knowledge into new indicators will be difficult, however.
Addressed by current indicators?	No. Emission inventories of POPs are lacking for many regions. Global-scale emission inventories are only available for a few POPs and such inventories may involve high uncertainties.	There are existing indicators that characterize long-range transport potential of POPs, e.g. Characteristic Travel Distance and Arctic Contamination Potential. There are no indicators that address impact on a local or regional scale. Temporal trends of POPs are usually assessed with their rates of decline in air or halflives (time required for the air concentration of a POP to decline to half its original value).	There is a lack of knowledge on the association of POPs with other pollutants. Better understanding of linkages between POPs in air and other co-pollutants will be beneficial in developing effective monitoring and control strategies for multiple pollutants. Generally, no, although speciated forms of mercury may warrant distinct consideration as their actions in the environment are different from each other.
Mercury	Complex global patterns of transport, deposition, and natural re-emission of mercury result in only coarse spatial and temporal correlation between ambient air concentrations, anthropogenic emissions, and environmental deposition. Indicators useful from a management perspective should focus on improved metrics describing human risk of exposure, which occurs primarily through seafood consumption and certain occupational tasks.		
Addressed by current indicators?	There are no consistent indicators to describe human risk exposure to mercury through seafood consumption and certain occupational tasks. A gap exists between what is measured at the source and the impact on human health.		

(Sources: Engel-Cox et al., 2013; Bowman, 2013; Hung et al., 2013; Pirrone et al., 2013).



representative zones common across typically-defined regions that face similar challenges with respect to POPs. By these sites Hung et al. (2013) distinguish between near source sites (e.g. industrial, agricultural, or urban centers); alpine sites; and remote sites. What is clear is that characterization and monitoring within these sites, as well as across geographic regions, is necessary for effective global assessment of POPs, and that management strategies may then be generalizable at both levels.

#### 4. Remaining policy needs and issues

Table 2 provides a brief summary of selected policy-relevant issues with respect to the design of the “next generation” of indicators for the four pollutants addressed in this special issue: PM, ozone, POPs, and mercury. The matrix details whether current indicators address these policy-relevant issues, where current indicators fall short, and what improvements should be made to develop better indicators that communicate to decision-makers and the public about the impacts of each pollutant.

For those pollutants for which air quality indicators are based on ambient air concentrations (PM and ozone), it is important to recognize that a combination of ambient monitoring along with modeling and characterization of emission inventories is necessary. The former allows decision makers and the public to gauge the absolute level of their air quality and its value relative to other locations and over time. The latter is required in order to attribute atmospheric concentrations to emission sources and enable more informed decisions about how to improve air quality. Evaluation of different policy options requires modeling of their effects on emissions and subsequently on atmospheric concentrations. Such modeling is only credible when the model can reproduce observed atmospheric abundances and the relationship between those concentrations and various emission sources. In other words, a synergistic interaction between observations and modeling is needed to understand the factors leading to degraded air quality in particular regions. That understanding can then be used to help determine optimal policies for improving air quality. The papers in this issue emphasize the monitoring and modeling requirements for “next generation” air quality indicators, which can both identify problems and motivate solutions, but the deeper process-level understanding aspects of observations and modeling discussed in the papers is also necessary for implementing successful policies to improve air quality.

Finally, while each of the technical papers in this issue address specific recommendations to improve monitoring and indicators for each pollutant considered, there are number of cross-cutting issues with respect to the development of air quality indicators more generally. The following is a list of remaining questions surrounding the development of refined air quality indicators which is applicable to the broader context of air quality-related indicators:

- How should performance be scored when local pollution concentrations may be strongly affected by sources outside the study area (i.e., regional, inter-continental, etc.)? A challenge with respect to designing a country-level performance index is the failure to adequately take into account the transboundary nature and effects of air pollution. How can indicators address this issue of “leakage” or transfers of pollution from urban to rural areas, from more polluted areas to those that are less polluted?
- What are the appropriate air quality levels countries should be striving to achieve, and are these better determined at the national or international level? While the WHO sets recommended levels for PM and ozone, there are no equivalent levels for POPs and mercury. In designing performance-based

metrics, a target or high and low performance benchmarks are required, but are there sustainable ambient limits for these pollutants that countries should be striving toward? Should indicators be weighted by their impacts, even if this approach results in a less straight-forward indicator (e.g. health impacts of PM vary non-linearly with concentration)?

- Is it more useful to provide an aggregate air quality index that spans a range of pollutants, or to disaggregate communication of air quality into multiple, single-pollutant based indices? While individual indicators of PM or ozone might make the most sense, separation of POPs is not feasible because even a single category is still comprised of multiple compounds. These considerations of the suitable level of detail and unit of analysis make the process of identifying consistent air quality indicators even more challenging if a broad-ranging composite index is desired.
- How should policymakers prioritize investments in monitoring technology? While satellite data provide complete spatial coverage relative to other data sources, such as ground-level monitors, satellites are costly to launch and maintain. Low-cost, high-confidence monitoring equipment are oft-cited needs of developing countries (CAI-Asia, 2012b). Further, satellite sensors deteriorate over time and are subject to failure. Height and Ferrier (2006) have found in case studies of air quality monitoring in developing countries that imported air-quality monitoring equipment was a critical component to the success of nearly all programs they evaluated. However, human capacity and personnel to properly operate equipment are also needed and require investments in capacity building and training. Therefore, even with technology in place, air quality could still be improperly assessed and poorly monitored if capacity is limited.

All of the recommendations in this issue are nonetheless subject to real-world economic, technical, and political constraints. Economic and technical constraints have been discussed above; political constraints are outside the scope of this paper. However, these considerations are still critical to understanding potential challenges in the development of the next generation of air quality indicators.

#### 5. Summary and final conclusion

This paper has provided an introduction to an effort initiated by YCELP, CIESIN, and AIEES, in collaboration with scientific and policy experts across the world, to discuss the next generation of air quality monitoring indicators for PM, ozone, mercury, and POPs.

This special issue forms the basis of recommendations for the design of new air quality indicators in general, and in particular for the next iteration of the EPI, which will be released in January 2014. Each subsequent scientific paper provides a necessary foundation by which to construct these indicators for inclusion in the 2014 EPI to provide a signal to policymakers with an understanding of the status of these pollutants in their respective countries. With this information, it is the hope that decision-makers will be able to take the necessary measures to formulate coordinated policies by which to manage these pollutants for improved global air quality.

#### Acknowledgements

We would like to thank our partners at the Asian Institute for Energy and Environment (AIEES) of Seoul National University for hosting the October 2012 workshop and providing generous backing for this research effort, in particular Prof. Ki-ho Kim.

Additionally, we would like to thank the staff and researchers at the Yale Center for Environmental Law and Policy for their support. We would also like to thank all of the scientific experts who contributed papers to this issue, as well as the participants who traveled to South Korea in October to participate and to provide feedback on the design of this project. We also thank an anonymous reviewer for their helpful comments on an earlier draft of this paper. Last, we would like to thank Kim Samuel, Chair of the Yale Center for Environmental Law and Policy Advisory Board, for her vision and continued support of the EPI throughout all of these years.

## References

- Bell, M.L., Hobbs, B.F., Ellis, H., 2005. Metrics matter: conflicting air quality rankings from different indices of air pollution. *Journal of the Air & Waste Management Association* 55 (1), 97–106.
- Bowman, K., 2013. Toward the next generation of air quality indicators: ozone. *Atmospheric Environment*.
- Bradshaw, G.A., Borchers, J.G., 2000. Uncertainty as information: narrowing the science-policy gap. *Conservation Ecology* 4 (1), 7.
- Brauer, M., Amman, M., Burnett, R.T., Cohen, A., Dentener, F., Ezzati, M., Henderson, S.B., Kryzhanowski, M., Martin, R.V., Van Dingenen, R., van Donkelaar, A., Thurston, G., 2012. Exposure estimate for the estimation of the global burden of disease attributable to outdoor air pollution. *Environmental Science and Technology* 46 (2), 652–660.
- Bruno, F., Cocchi, D., 2002. A unified strategy for building simple air quality indices. *Environmetrics* 13 (3), 243–261.
- Clean Air Initiative – Asia (CAI-Asia), 2012a. Accessing Asia: Air Pollution and Greenhouse Gas Emissions from Road Transport and Electricity. Clean Air Asia, Pasig City, Philippines. Available: <http://cleanairinitiative.org/portal/node/11573> (last accessed 28.02.13.).
- Clean Air Initiative – Asia (CAI-Asia), 2012b. Interview. July 27.
- Dimitrov, R.S., 2003. Knowledge, power, and interests in environmental regime formation. *International Studies Quarterly* 47, 123–150.
- Emerson, J.W., Hsu, A., Levy, M.A., de Sherbinin, A., Mara, V., Esty, D.C., Jaiteh, M., 2012. Environmental Performance Index and Pilot Trend Environmental Performance Index. Yale Center for Environmental Law and Policy, New Haven.
- Engel-Cox, J., Oanh, K., van Donkelaar, A., Martin, R., Zell, E., 2013. Toward the next generation of air quality monitoring: particulate matter. *Atmospheric Environment*.
- Ezzati, M., Kammen, D.M., 2002. The health impacts of exposure to indoor air pollution from solid fuels in developing countries: knowledge, gaps, and data needs. *Environmental Health Perspectives* 110 (11), 1057.
- Frosch, D., 23 February 2013. Seen as Nature Lovers' Paradise, Utah Struggles with Air Quality. *The New York Times*. Available: [http://www.nytimes.com/2013/02/24/us/utah-a-nature-lovers-haven-is-plagued-by-dirty-air.html?\\_r=1&](http://www.nytimes.com/2013/02/24/us/utah-a-nature-lovers-haven-is-plagued-by-dirty-air.html?_r=1&) (last accessed 28.02.13.).
- Group on Earth Observations, 2010. GEO Task US09-01a: Earth Observation Priorities for Health SBA – Air Quality Sub-area. Available: [sbageotask.larc.nasa.gov/AirQuality\\_US0901a-FINAL.pdf](http://sbageotask.larc.nasa.gov/AirQuality_US0901a-FINAL.pdf) (last accessed 28.02.13.).
- Hammond, A., Adriaanse, A., Rodenburg, E., Bryant, D., Woodward, R., 1995. Environmental Indicators: a Systematic Approach to Measuring and Reporting on Environmental Policy Performance in the Context of Sustainable Development. World Resource Institute. Report.
- Height, J., Ferrier, G., 2006. The Impact of Monitoring Equipment on Air Quality Management in Developing Countries. OECD Trade and Environment Working Paper No. 2006-02. Organisation for Economic Cooperation and Development, Paris.
- Hung, H., Guardans, R., Barra, R., MacLeod, M., Scheringer, M., Harner, T., Zhang, G., 2013. Toward the next generation of air quality indicators: persistent organic pollutants (POPs). *Atmospheric Environment*.
- Kinne, S., Lohmann, U., Feichter, J., Schulz, M., Timmreck, C., Ghan, S., Kaufman, Y., 2003. Monthly averages of aerosol properties: a global comparison among models, satellite data, and AERONET ground data. *Journal of Geophysical Research* 108 (D20), 4634.
- Levy, M.A., 1993. European acid rain: the power of tote-board diplomacy. In: *Institutions for the Earth: Sources of Effective International Environmental Protection*, pp. 75–132.
- Levy, M.A., 1995. International co-operation to combat acid rain. In: *Green Globe Yearbook*, pp. 59–68.
- Lim, Stephen S., et al., 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the global burden of disease study 2010. *The Lancet* 380 (9859), 2224–2260.
- Mage, D., Ozolins, G., Peterson, P., Webster, A., Orthofer, R., Vandeweerd, V., Gwynne, M., 1996. Urban air pollution in megacities of the world. *Atmospheric Environment* 30 (5), 681–686.
- McNie, E., 2006. Reconciling the supply of scientific information with user demands: an analysis of the problem and review of the literature. *Environmental Science & Policy*, 10, 17–38.
- McKinsey Global Institute (MGI), 2009. Preparing for China's Urban Billion. Available: [http://www.mckinsey.com/insights/urbanization/preparing\\_for\\_urban\\_billion\\_in\\_china](http://www.mckinsey.com/insights/urbanization/preparing_for_urban_billion_in_china) (last accessed 25.07.13.).
- Ott, W.R., Hunt Jr., W.F., 1976. A quantitative evaluation of the pollutant standards index. *Journal of the Air Pollution Control Association* 26 (11), 1050–1054.
- Peterson, P.J., Williams, W.P., 1999. New indicator approaches for effective urban air quality management. *Environmental Science and Pollution Research* 6 (4), 225–232.
- Pirrone, N., Aas, W., Cinnirella, S., Ebinghaus, R., Hedgecock, I.M., Pacynab, J., Sproveric, F., Sunderland, E.M., 2013. Toward the next generation of air quality monitoring: mercury. *Atmospheric Environment*.
- POINT, 2011. A Synthesis of the Findings of the POINT Project. No. 15. In: *POINT Policy Use and Influence of Indicators – Current Use of and Emerging Needs for Indicators in Policy*. The Bayswater Institute.
- Polfeldt, T., 2006. Making environment statistics useful: a third world perspective. *Environmetrics* 17 (3), 219–226.
- Pope III, C.A., Ezzati, M., Dockery, D.W., 2009. Fine-particulate air pollution and life expectancy in the United States. *New England Journal of Medicine* 360 (4), 376–386.
- Radermacher, W., 2005. The reduction of complexity by means of indicators – case studies in the environmental domain. In: *Statistics, Knowledge Policy: Key Indicators to Inform Decision Making*. OECD, Paris.
- Seto, K.C., Guneralp, B., Hutyrac, L.R., 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *PNAS*. <http://dx.doi.org/10.1073/pnas.1211658109>.
- Srebotnjak, T., 2007. The role of environmental statisticians in environmental policy: the case of performance measurement. *Environmental Science & Policy* 10, 405–418.
- Smith, K.R., Mehta, S., 2003. The burden of disease from indoor air pollution in developing countries: comparison of estimates. *International Journal of Hygiene and Environmental Health* 206 (4), 279–289.
- Smith, S.J., van Aardenne, J., Klimont, Z., Andres, R.J., Volke, A., Delgado Arias, S., 2011. Anthropogenic sulfur dioxide emissions: 1850–2005. *Atmospheric Chemistry and Physics* 11, 1101–1116.
- United Nations (UN), 1992. In: *Agenda 21. Proc. of United Nations Conference on Environment & Development, Brazil, Rio De Janeiro*. Available: <http://sustainabledevelopment.un.org/content/documents/Agenda21.pdf> (last accessed 28.12.12.).
- United Nations Environment Program (UNEP), 2012. Chapter 6 chemicals and waste. In: *GEO-5 Global Environmental Outlook 5 Assessment Report*. Progress Press Ltd, Malta, pp. 168–192. <http://www.unep.org/geo/geo5.asp>.
- US Environmental Protection Agency (USEPA). Available: *GEMS/AIR* (WHO information). <http://www.epa.gov/ttnamti1/archive/gems.html> (last accessed 20.01.13.).
- van Donkelaar, A., Martin, R.V., Brauer, M., Kahn, R., Levy, R., Verduzco, C., Villeneuve, P.J., 2010. Global estimates of exposure to fine particulate matter concentrations from satellite-based aerosol optical depth. *Environmental Health Perspectives* 118 (6), 847–855. <http://dx.doi.org/10.1289/ehp.0901623>.
- Wong, E., 12 January 2013. On a Scale of 0 to 500, Beijing's Air Quality Tops 'Crazy Bad'. *The New York Times*. [http://www.nytimes.com/2013/01/13/science/earth/beijing-air-pollution-off-the-charts.html?\\_r=0](http://www.nytimes.com/2013/01/13/science/earth/beijing-air-pollution-off-the-charts.html?_r=0) (last accessed 25.01.13.).